and migration of gases into atmosphere. The gas emission into atmosphere in the areas of rich gas fields may dramatically influence the global changes of climate, favoring development of green house effect.

Shore erosion is a source of sediments coming into the sea from the land. Therefore it plays a part in formation of Arctic sea sediment balance. But the importance of this part is not determined reliably till now. For a long time the sediment discharge of rivers was considered in Russia as the main terrestrial input into the sediment balance of the seas. Suzdalsky (1974) made a very rough comparison of river and shore input into White, Barents and Kara Seas and obtained values of the same order. He pointed out the necessity of further investigations. Shuyski (1983) made a new but also very rough evaluation and came to the conclusion that abrasion of sea shores and shore faces brings to the World Ocean as many sediments as the river transport to their mouths.

At present it is possible to determine the input of shore erosion into the sediment balance of Arctic seas more accurately than in previous attempts. The main goal of this paper is to evaluate the input of coastal erosion into the sediment balance of Laptev Sea. For this purpose we need the data on shore retreat rate (V, m/y), height of the cliffs (H, m), water depth at the lower boundary of the shore face, lithology of sediments composing the coast, volumetric ice content of these sediments and their dry bulk density.

Among the parameters listed the least studied and understood is the lower boundary of the shore face, which corresponds to the average maximum wave base, that is, the maximum depth of wave influence on the bottom (h_{max}, m). This boundary is usually well-defined geomorphologically in deep seas (the depths > h_{max}) along the abrasion coasts composed of sand or coarse-grained sediments or rocks. In such situation the wave base is marked by the brow of a underwater accretion terrace (Figure 1) (Zenkovich, 1962). In shallow seas the lower boundary of shore face may be associated with the izobath where the comparatively steep slope of shore face changes into a rather gentle slope of transition zone. However, in some beach profiles the change of inclination is indistinguishable. In some areas the boundary between shore face and transition zone may be determined by the change of bottom sediments: sandy on the shore face and silty in transition zone (Reineck and Singh, 1980). In some seas, as for example the Laptev Sea, the waves influence the bottom on the major part of its area. In this situation the notion of shore face is useless.

Nevertheless, it is necessary to choose the position of boundary between the area of shore erosion and the area of sea floor erosion for calculating the sediment amount supplied into the

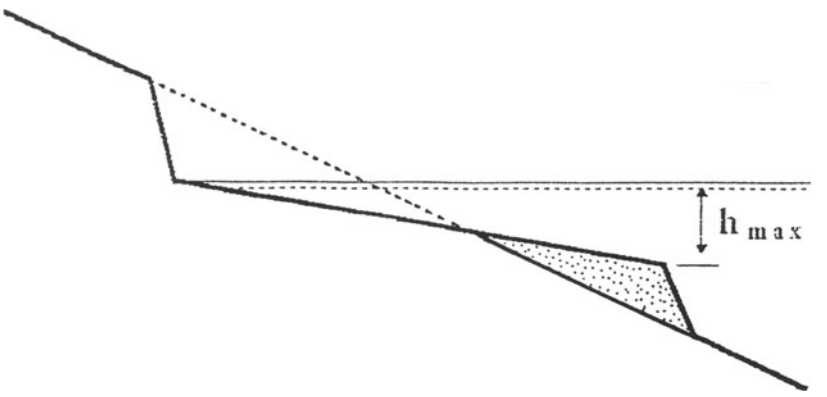

Figure 1: The scheme of bench-like profile for abrasion shore by high bathymetric gradient offshore from accretion terrace. h_{max} - the depth of wave influence on the bottom.

sea by destruction of the shores. At present we can only use an assumed maximum depth for the shore face supplying the sea with sediments. This approach can not be substantiated reliabl, because of a lack of real data. For a better approach repeated bathymetric surveys with sufficiently long time intervals are needed first of all. Such data exist (Kluyev, 1970) and they have to be used in future investigations.

Most data on the shore retreat rate of Arctic seas are published by Are (1985), Reimnitz at al. (1988) and Barnes et al. (1991). The height of coastal bluffs may be obtained from topographic maps at 1:25 000 scale. Satisfactory data on lithology of coastal sediments are presented on geological maps of 1:1 000 000 and larger scales. The Map of Yakutia permafrost landscapes of 1:2 500 000 scale gives but a rough idea of the coastal sediment ice content. The height of the cliffs and near shore bathymetry may be obtained from the topographic maps of 1: 25 000 and other scales. Various additional data may be found in numerous scientific publications. Actual field observations would of course be of great importance.

Methodology of determination of shore erosion input into the sediment balance of the Laptev Sea

The quantity of sediments supplied to the sea by shore erosion may be calculated on the base of two different principal ideas. The classical theory of abrasion supposes that the retreat of abrasion shore has a limit determined by the minimum inclination of the shore face (Zenkovich, 1962). The volume of the coast section eroded according to this idea is shown in Figure 2. Thus the annual volume on 1 m length of the shore may be calculated as follows

$$W = (F_1 + F_2) \cdot 1 = V \cdot H + 0.5\ V \cdot h_{max} = V\ (H + 0.5\ h_{max})$$

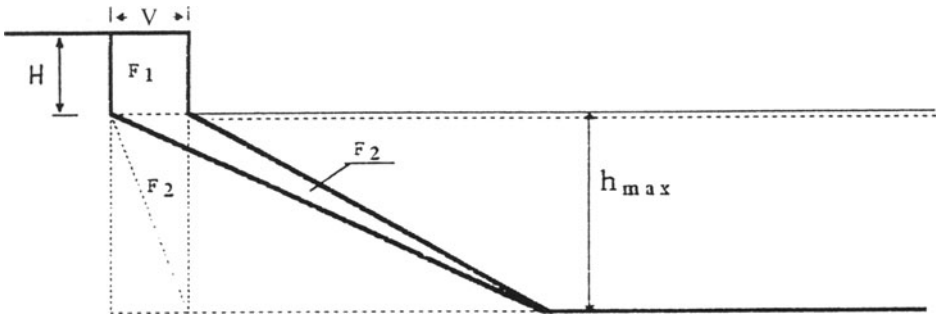

Figure 2: The scheme of flat shore face transformation by limited retreat of shallow sea shore.

The second idea supposes continuous retreat of the shore at comparatively constant rate. Such kind of retreat is observed on many sections of Arctic sea coasts during last decades. The profile of shore face retreats parallel to itself in this case with the same rate as the shore line (Figure 3). The volume of coast section eroded per meter of shoreline now will equal

$$W = (F_1 + F_2) \cdot 1 = V \cdot H + V \cdot h_{max} = V\ (H + h_{max})$$

It is important that by continuous retreat the volume of material coming from the shore face is two times larger than by limited retreat.

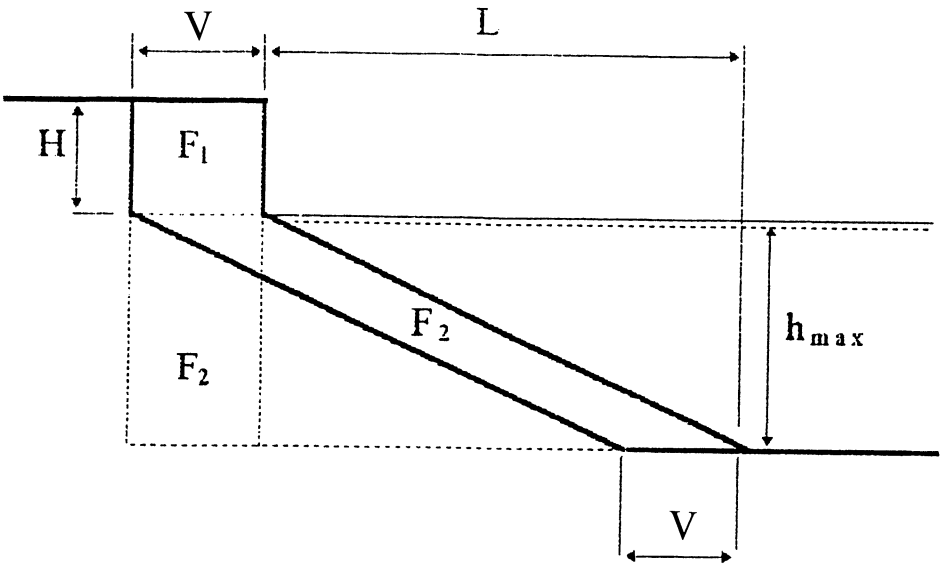

Figure 3: The scheme of flat shore face transformation by continuous retreat of shallow sea shore.

Very simple geometrical considerations show that volume of sediments supplied to the sea by erosion of the shore face do not depend on inclination and form of it. This is true for both continuous and limited retreat. Figure 4 shows the scheme of unlimited retreat of concave shore face. The volume of shore face section eroded according to this scheme is

$$W = V \cdot h_1 + V \cdot h_2 + V \cdot h_3 = V (h_1 + h_2 + h_3) = V \cdot h_{max}$$

So the result is the same as for the flat shore face retreat (Figure 3).

The scheme of limited retreat of flat and concave shore faces is shown in Figure 5. The volume of coast section eroded for both forms of shore face may be calculated as follows.
Concave shore face:

$$W = 0.5 (V + a_1) h_1 + 0.5 a_1 + a_2) h_2 + 0.5 \cdot a_2 \cdot h_3$$

Flat shore face:

$$W = 0.5 \cdot V \cdot h_{max} = 0.5 (V + a_1) h_1 + 0.5 (a_1 + a_2) h_2 + 0.5 \, . \, a_2 \, . \, h_3$$

So in both cases the eroded volume is determined by the sum of the areas of two trapeziums and one triangle which are equal in pairs.

In any case the eroded volume is determined by the sum of the areas F_1 and F_2 (Figures 2 and 3) as well as by retreat of a vertical wall having the height equal $H + h_{max}$. So the V, H and h_{max} are the geometrical parameters needed for calculating of volume eroded. The width of shore face L (Figure 3) is not needed.
The reasonable choice of h_{max} value will depend on local bathymetrical conditions. US scientists calculating the volume of eroded sediments for the western part of Alaska Beaufort Sea coast used h_{max} = 2 m at first because a pronounced, and widespread break in slope marks

the outer boundary of a shore bench at this depth (Reimnitz et al., 1988). Later on they came to the conclusion that the shore erosion reaches the 6 m isobath and possibly still deeper (Barnes et al., 1991).

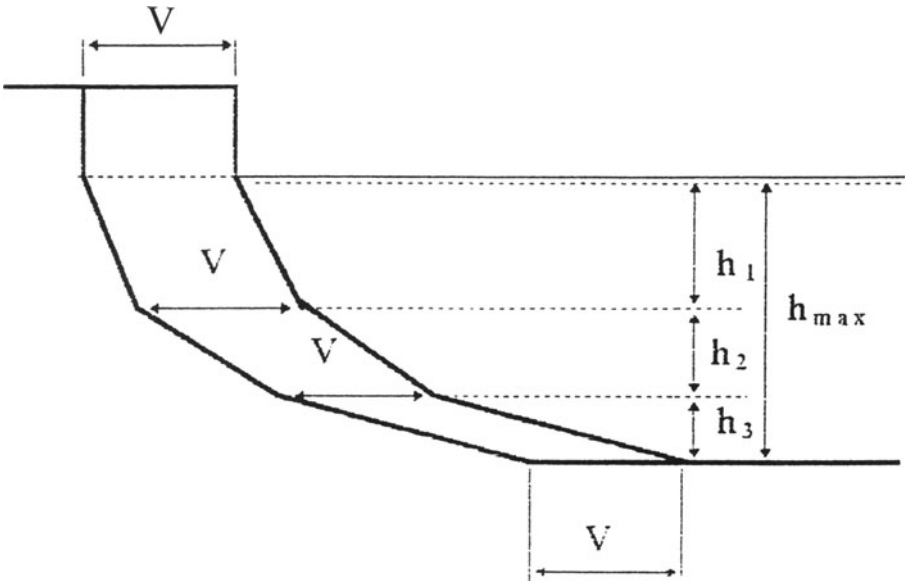

Figure 4: The scheme of concave shore face transformation by continuous retreat of shallow sea shore.

Amount of sediments supplied to the sea by retreat of Anabar-Olenyok section of the coast

Kluyev compared bathymetric profiles till 5 m isobath along the Anabar-Olenyok coast (160 km) obtained in 1942-43 and in 1962-64. This isobath is situated at a distance of 6-8 km from the shore. The results of comparison showed that erosion of the bottom is taking place everywhere in this area at a rate as high as 4 cm/y (Kluyev, 1967, 1970; Kluyev and Kotykh, 1985). About the same situation is observed in the cape Krestovsky area of the East-Siberian Sea out to the 6 m isobath despite of very low bathymetric gradient of 0.0003. Changes of bottom relief in deeper parts of the seas were not investigated.

In Kluyev's opinion, the retreat rate of shores and the form of the underwater slope in above mentioned areas do not change with time. So the slope retreats parallel to itself. This means that the volume of eroded sediments has to be calculated in accordance with the idea of continuous retreat at least for the sections of shores investigated by Kluyev.

Noteworthy is the fact that according to Kluyev the bottom of the seas is composed of sand in the area between 4-6 and 20-25 m isobaths, and is silty outside of this depth range. The coastal plains in the sections investigated by Kluyev are composed by ice complex ("yedoma") - perennially frozen fine-grained Quaternary sediments with high ice content and with inclusions of large ice wedges. The usual total ice content in these sediments is in the range of 60-80 % by volume. The granulometric composition is characterized by 60-80 % of particles less then 0.05 mm in diameter. So the absence of these particles may be caused by wave erosion of the bottom in the above zone.

The Anabar-Olenyok coast is one of the longest and comparatively well studied sections of

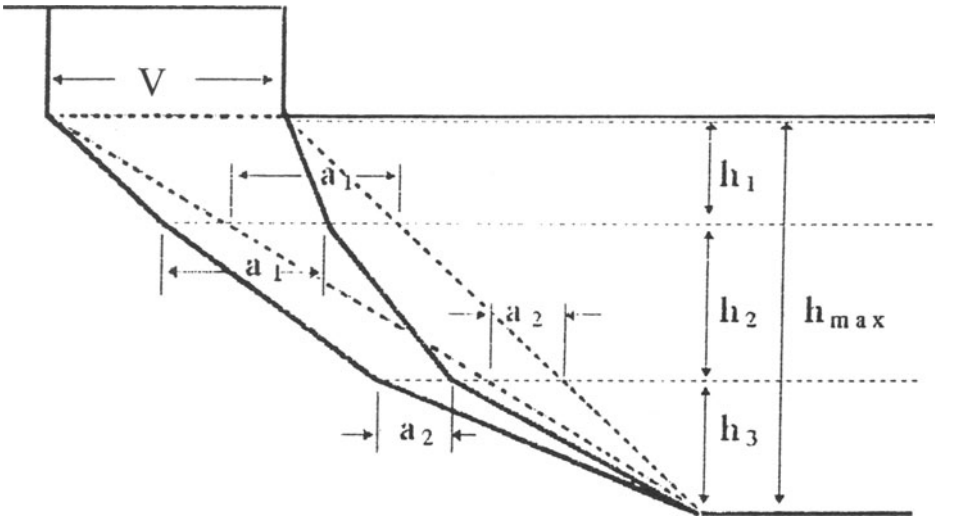

Figure 5: The scheme of concave shore face transformation by limited retreat of shallow sea shore.

retreating shores in the Laptev Sea (Figure 6). The rates of retreat were determined by means of comparison of aerial photographs taken in 1949 and 1971. The scales of photographs were 1:36 000 and 1:84 000. The comparison was performed without any special apparatus. The lowest retreat rate which could be reliably determined using this procedure was about 0.5 m/y. The mean rate of shore retreat for the 85 km of the coast in Figure 6 is about 2 m/y.

A part of the coast 69.5 m long is composed by ice complex or thermokarst depression deposits. The latter are composed mainly of the thawed and subsided ice complex. Therefore the height of the cliffs crossing thermokarst depressions may be considered as the result of thaw settlement of ice complex for the first approach. Accepting this viewpoint means that the quantity of sediments supplied to the sea by erosion of cliffs composed of ice complex and thermokarst depression deposits per meter of shoreline is equal. So there is no need to calculate the quantity of mineral components in ice complex using values of ice content. All shore composed by ice complex or thermokarst depression deposits may be considered as having the height of the cliffs equal to the height of cliffs in thermokarst depressions (10 m).

Little is known about the thickness of ice complex in this area. In some places the lower ends of ice-wedges are below sea level. For the first approach it is assumed that thaw settlement of all deposits which occur below sea level is zero. According to Kluyev the retreat of shores is continuous and the maximum depth of erosion is at least 5 m (actually it is larger). The dry bulk density of silty sands is approximately 1.5 t/m^3.

Using the data listed, the mass of sediments supplied to the sea due to erosion of 69.5 km of the shore will be

$$M = ß \cdot V\,(H + h_{max}) \cdot D = 1.5 \cdot 2\,(10 + 5) \cdot 69\,500 = 3\,127\,500 \text{ t/y},$$

where ß is the dry bulk density of thawed sediments, D - the length of the section of coast.

A 15.5 km long part of the coast presented in Figure 6, with the cliffs up to 1 m high is composed of fine-grained sands with low ice content giving no thaw settlement. The mass of sediments coming from this section will be

$$M = 1.5 \cdot 2 \cdot (0.5 + 5) \cdot 15\,500 = 255\,750 \text{ t/y}$$

Thus the total sediment yield from 85 km long retreating coastal sector is about 3.4 Mt/y.

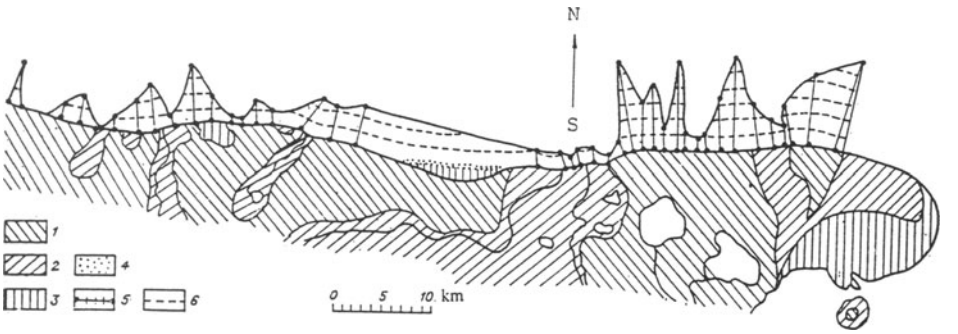

Figure 6: Mean annual shore retreat rate for 22 years (1949-1971) along 85 km of Anabar-Olenyok coast, Laptev Sea (Are, 1985). (1) - ice complex, height of cliffs 30-40 m; (2) - thawed ice complex in the thermocarst lake depressions, height of cliffs 8-12 m; (3) - surfaces up to 1 m high; (4) - inter tidal surfaces; (5) - graph of the shore retreat rate, m/y; (6) - isometric lines of shore retreat rate values at a spacing of 1 m/y.

Sediment discharge of rivers draining into the Laptev Sea

Let us compare the results of calculations of the Anabar-Olenyok coast input into the sediment balance of Laptev Sea with the data on sediment discharge of the rivers. The monitoring of water and sediment discharge of rivers flowing into the Laptev Sea is carried out during last decades. One of the earliest results is presented in Table 1. The points of sediment discharge monitoring listed in the Table 1 are situated upstream from the mouths and deltas of the rivers at the distances as far as 200-300 km. So the numbers in Table 1 do not represent the total riverine sediment supply to the Laptev Sea.

The results of latest generalization are published by Ivanov and Piskun (1995). These investigators evaluate the mean sediment discharge of the Lena river at 18.4 Mt/y in Kyusyur. They believe that the total discharge in delta channels is larger due to erosion of shores and reaches 19.4 Mt/y. The sediment discharge of Olenyok and Yana rivers makes up 1.48 and 4.19 Mt/y respectively. Ivanov and Piskun emphasize that all data available characterize the sediment discharge in the river or its delta but not the amount of sediments coming into the sea. To estimate the input of rivers into sediment balance of the sea special full-scale investigations are needed. The same authors give the value of suspended sediment discharge in the main Lena river channel 4.7 km upstream from Stolb island as large as 517 kg/s which is equal 16.3 Mt/y (this volume).

Recent data of Moscow State University investigators presented in Table 2 give another version of river sediment discharge values. These data belong to the upper margins of deltas. Alabyan et al. state, that only 2.1-3.5 Mt/y from the total Lena river suspended sediment discharge enter the sea. The major part of sediments according to them accretes in the vast delta

plain. But unfortunately in the publication cited no reason is given for this extremely important statement.

Noteworthy is that one of the authors of the latter publication, Korotayev, gives the value of Lena sediment discharge at the apex of delta as large as 12 Mt/y in another book (Tshalov et al., 1995).

Table 1: Sediment transport of Yakutian rivers (Doronina, 1962).

River	Point	Years	Mean turbidity		Sediment discharge
			g/m^3	t/km^3	Mt/y
Anabar	Saskylakh	1936	14.3	14 300	0.235
Olenyok	Kuoyka	1938-40	15	15 000	0.535
Lena	Kyusyr	1936-44	23.1	23 100	11.804
Yana	Yuttakh	1938-41	200	200 000	6.360

Table 2: Water and sediment discharge of the rivers flowing into the Laptev Sea (Alabyan et. al., 1995).

River	Water discharge	Sediment discharge
	km^3/y	Mt/y
Anabar	13.2	0.4
Khatanga	101	1.4
Lena	520	21
Yana	30.7	3
All rivers	700	26

Conclusions

The calculation of the sediment supply to Laptev Sea due to Anabar-Olenyok coastal retreat and comparison of this amount with the input of Yakutian rivers shows that these two parts of sediment balance of the Laptev Sea are at least of the same order. The input of shore erosion may be even larger because the total length of erosional shores of the Laptev Sea makes up approximately 1000-1300 km, that is 12-15 times longer than the 85 km Anabar-Olenyok coastal section considered.

Acknowledgments

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References

Alabyan, A.M., R.S. Chalov, V.N. Korotayev, A.Yu. Sidorchuk and A.A. Zaitsev (1995) Natural and technogenic water and sediment supply to the Laptev Sea. Berichte zur Polarforschung, 176, AWI, Bremerhaven, BRD, 265-271.

Are, F.E. (1985) Osnovy prognoza termoabrazii beregov (Principles of shore thermoabrasion forecast). -Novosibirsk, Nauka Publ., 172 pp.

Barnes, P.W., E. Reimnitz, and B.P. Rollyson (1991) Map of Beaufort Sea coastal erosion and accretion, north-eastern Alaska. U.S. Geological Survey. Miscellaneous Investigations, Map 1182-4.

Doronina, N. A. (1962) Reki (The rivers). In: Severnaya Yakutia. Transactions of AARI, vol. 236, Leningrad. Morskoy transport Publ, 193-222.

Houghton, J.T. et al. (1996) Climate change 1995, Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 572 pp.

Ivanov, V.V. and A.A. Piskun (1995) Distribution of river water and suspended sediments in the river deltas of the Laptev Sea. Berichte zur Polarforschung, 176, AWI, Bremerhaven, BRD, 142-153.

Kluyev, Y.V. (1967) Rol merzlotnyh faktorov v dinamike relyefa dna polyarnyh morey (The role of cryogenic factors in dynamics of bottom relief of polar seas). Author abstract of candidate theses, geographical sciences. Petersburg State University,12 pp.

Kluyev, Y.V. (1970) Termicheskaya abraziya pribreznoy polosy polyarnyh morey (Thermal abrasion of near shore zone of polar seas). Izvestiya vsesoyuznogo geograficheskogo obshchestva, vol. 102, vypusk 2, 129-135.

Kluyev, Y.V. and Kotyukh (1985) Some peculiarities of the dynamics of the relief of the bed of the Laptev Sea. - Polar Geography and Geology, vol. 9/4, 301-307.

Reimnitz , E., S.M. Graves and P.W. Barnes (1988) Beaufort Sea coastal erosion, sediment flux, shoreline evolution, and the erosional shelf profile. U.S. Geological Survey. To accompany Map I-1182-G, 22 pp.

Reineck, H.-E. and I.B. Singh (1980) Depositional sedimentary environments. Springer-Verlag, 549 pp.

Suzdalsky, O.V. (1974) Litodinamika melkovodja Belogo, Barenceva i Karskogo morey (Lythodynamics of White, Barents and Kara Sea shallows). In: Geologiya morya (Sbornik statey), vypusk 4, NII geologii Arktiki, 27-33.

Shuyski, Y.D. (1983) Sovremenny balans nanosov v beregovoy zone morya (Recent sediment balance in the shore zone of the sea). Author abstract of doctor theses, geographical sciences. Moscow State University, 41 pp.

Tshalov, R.S., V.M. Panchenko and S.Y. Zernov (1995) Vodnye puti basseyna Leny (Waterways in the Lena river basin). Moskva, MIKIS, 600 pp.

Zenkovich, V.P. (1962) Osnovy ucheniya o razvitii morskih beregov (The foundations of teaching on sea shore evolution). Moskva, Izdatelstvo Akademii nauk SSSR, 710 pp.

Zigarev, L.A. and V.A. Sovershaev (1984) Termoabrazionnoe razrushenie arkticheskih ostrovov (Thermoabrasional destruction of Arctic islands). In: Beregovye processy v kriolitozone. Novosibirsk: Nauka, 31-38.